Improved design of an overhead rail current conductor for application in underground lines

C. Vera, J. Paulin, B. Suarez, P. Rodriguez

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IMPROVED DESIGN OF AN OVERHEAD RAIL CURRENT CONDUCTOR FOR APPLICATION IN UNDERGROUND LINES

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KEYWORDS: Catenary and electrification systems, overhead conductor rail systems, optimisation, new design

ABSTRACT

Overhead rail current collector systems for railway traction offer certain features, such as low installation height and reduced maintenance, which make them predominantly suitable for use in underground train infrastructures. Due to the increased demands of modern catenary systems and higher running speeds of new vehicles, a more capable design of the conductor rail is needed.

A new overhead conductor rail has been developed and its design has been patented [13]. Modern simulation and modelling techniques were used in the development approach. The new conductor rail profile has a dynamic behaviour superior to that of the system currently in use. Its innovative design permits either an increase of catenary support spacing or a higher vehicle running speed. Both options ensure savings in installation or operating costs.

The simulation model used to optimise the existing conductor rail profile included both a finite element model of the catenary and a three-dimensional multi-body system model of the pantograph. The contact force that appears between pantograph and catenary was obtained in simulation. A sensitivity analysis of the key parameters that influence in catenary dynamics was carried out, finally leading to the improved design.

INTRODUCTION

In recent years the demand of new railway installations in cities all over the world has increased significantly. High running speeds are needed in order to deal with the growing number of passengers to be transported. Detailed studies of the pantograph-catenary interaction are required so that both a proper catenary system and an appropriate pantograph can be chosen.

In this sense, modelling and simulating tools can be of great use when analysing already existing systems or when developing new designs. By means of these techniques it is possible to perform sensitivity studies, which facilitate the optimisation of new systems as well as the improvement of existing ones. This feature makes theses tools really useful.

The present paper shows the work undertaken by the Railway Technology Research Centre (CITEF – Centro de Investigación en Tecnologías Ferroviarias) of the Polytechnic University of Madrid (UPM – Universidad Politécnica de Madrid) in collaboration with Madrid Underground's Engineering Department (Metro de Madrid). The aim of this project was the development of a new overhead conductor rail that had a dynamic behaviour superior to that of the classic conductor rail primarily installed in Madrid's underground lines. The new design allows either an increase in the distance between catenary supports, at this time separated by 10 m, or an increase in running speed, which at present does not exceed 110 km/h. Both options lead to saving in overall costs: reduction of installation costs in the first case and reduction of exploitation costs in the second.

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As mentioned before, this work has been realised by means of advanced simulation techniques. Particularly, the ANSYS program was used for finite element modelling, and the SIMPACK program for multibody systems analysis.

OVERHEAD CONDUCTOR RAIL CURRENT COLLECTION FOR RAILWAY TRACTION

Main features

The classic overhead conductor rail [3-7, 9-12, 23] consists of two solidly joined conductor elements: an aluminium conductor rail and a copper contact wire.

The catenary cross section (Fig. 1) remains unchanged along all of its length. The aluminium conductor rail has a hollow pentagonal shape that presents an opening in the lower end consisting of two clamping arms or flanges, which hold the contact wire. Both flanges support the contact wire firmly along its grooves, retaining it through elastic deflection pre-stressing. This way, a correct fastening between both elements is ensured.

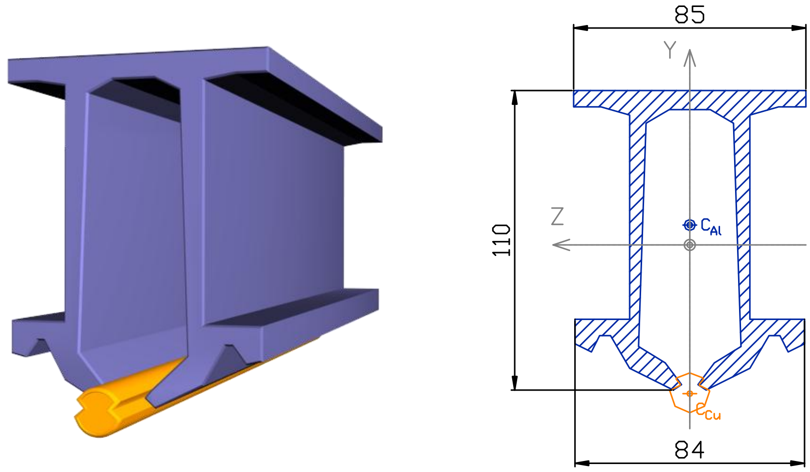

Fig. 1. Classic overhead conductor rail (3-D view and cross section)

Pieces of the conductor rail with a nominal length of 10 m, which may vary between 5 and 12 m, are manufactured by aluminium extrusion. These pieces are connected to each other by means of joint elements, called bridles, thus forming longer spans up to 500 m, called overlap sections.

Between two adjoining overlap sections a mechanical discontinuity is introduced, which allows for the free thermal expansion of both ends. If electrical continuity is required, the two overlap sections can be shortcut. In order to guaranty continuity throughout the passing of the pantograph, the ends of both sections overlap longitudinally. The ends of each section are curved upwards so that a smooth passing of the pantograph is guaranteed.

The overhead conductor rail is suspended from the tunnel roof by means of supports. The distance between these catenary supports is equal to the length of the aluminium pieces (currently 10 m). During the installation process, the supports are placed to either side of the centre of the track, giving the conductor rail a sinusoidal shape in the horizontal plane. This configuration, known as ‘stagger’, spreads the wear uniformly across the width of the pantograph’s contact strips.

Advantages and disadvantages

The overhead conductor rail system disposes of a set of advantages in comparison to other electrification systems. The main advantages offered by this system are:

- The simplicity and robustness of its components, simplifying installation and maintenance.
- The considerable height above the track, reducing the risk of accidental contact.

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- The reduced installation height required (due to the absence of the conventional catenary wire as well as to the simplicity of its supports).
- The absence of tensile forces in the contact wire, reducing the critical section for worn contact wires and increasing the mean time interval between wire replacements (in case of overhead conductor rail installations, the contact wire is usually not replaced until its section is so small that the pantograph's collector strips touch the aluminium profile).
- The great surface area, improving the system's own refrigeration and lowering the risk of melting by overheating.
- The great conductor section, allowing high current intensities and eliminating the necessity of feeders (therefore, overhead conductor rail systems are suitable for low electric voltages).

Maybe the best known advantage is the one of the reduced installation height required. This advantage makes overhead conductor rail systems so interesting for their application in tunnels, and these systems are increasingly being chosen for city underground systems as well as for main line tunnels.

Despite of all the advantageous properties, overhead conductor rail systems have some significant disadvantages:

- The absence of tensile forces in the contact wire, in combination with the high linear weight of the conductor rail, causing great static deflections of the catenary. These deflections are harmful to the system's dynamics, and are usually limited by reducing the distance between supports.
- This same phenomenon prevents high running speeds from being reached.

For the classic overhead conductor rail previously described, only running speeds up to 110 km/h can be reached when the distance between supports is 10 m. When increasing the supports' distance to 12 m, the maximum running speeds drops to 70 km/h. Both support spacing and running speed are subject to being improved by the new design presented in this paper.

STUDY STAGES

The following stages were passed throughout the study:

<u>A) Analysis stage</u>

- Construction of two separate models for catenary and pantograph.
- Validation and experimental fitting of both models.
- Merging of the models into one complete model that includes the pantograph-catenary interaction.
- Simulation of the system's dynamic behaviour and carrying out a sensibility study.
- Gathering of conclusions from the simulation results.

<u>B) Design stage</u>

- Design of a new catenary system whose characteristics would be superior to that of the classic system currently in use. For this purpose, conclusions obtained from the former simulations were applied.
- Simulation of the static and dynamic behaviour of the newly developed conductor rail catenary system, and comparison with the classic one.
- Fitting of standard elements (bridles, section insulators, etc.) to the new designed profile.

<u>C) Testing stage</u>

- Patent application for the new design (applicant: Metro de Madrid).
- Prototype manufacturing (Metro de Madrid).
- Test section installation (Metro de Madrid).

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- Test measurements performing.

ANALYSIS STAGE – DEVELOPMENT OF CATENARY AND PANTOGRAPH MODELS

Model construction

- *Catenary model*: Bearing in mind its elastic behaviour, the catenary model was directly generated in ANSYS. Conductor rail, contact wire and bridles were modelled by one-dimensional finite elements. Supports were modelled with spring-damper elements. The first eigen-frequencies and eigen-modes were imported into the multibody systems simulation program, SIMPACK, where the effect of the interaction with the pantograph was defined. In the latter program, other features of the catenary were defined, such as stagger from the track centre line and overlap sections.
- *Pantograph model:* A three-dimensional pantograph model was developed, that included all the features of the real mechanism. The final model thus presented four degrees of freedom: the raising of the pantograph mechanism and the bouncing, rolling and pitching movements of the pantograph head.
- *Interaction between both components*: The contact conditions between the contact wire and the pantograph head were defined, using the values proposed in [19]. In all models, the pantograph moves forward with constant speed of 110, 140 or 150 km/h.

Fig. 2 shows the complete pantograph-catenary model used in this work.

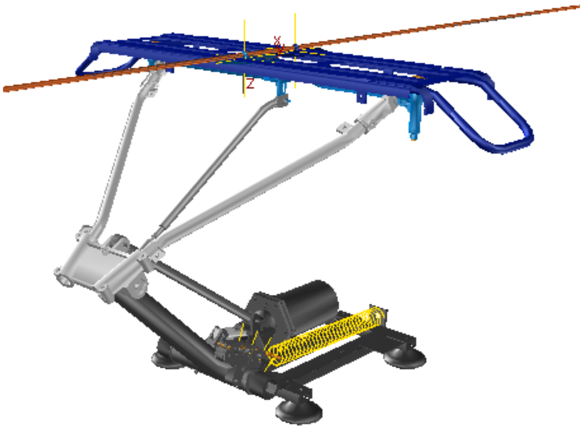

Fig. 2. Complete pantograph-catenary model (showing only the contact wire)

Model fitting and validation

Experimental measurements were carried out over the classic overhead conductor rail installed in Metro de Madrid. These tests were used to fit the unknown parameters related to the catenary system, such as the supports’ vertical stiffness, the structural damping, etc. It should be mentioned that the structural damping was found to be negligible.

Laboratory tests were also performed on a real pantograph, focussed on determining the damping of the head suspension system, as well as the friction damping in the joints. Fig. 3 shows a comparison between the experiment and the validated pantograph model.

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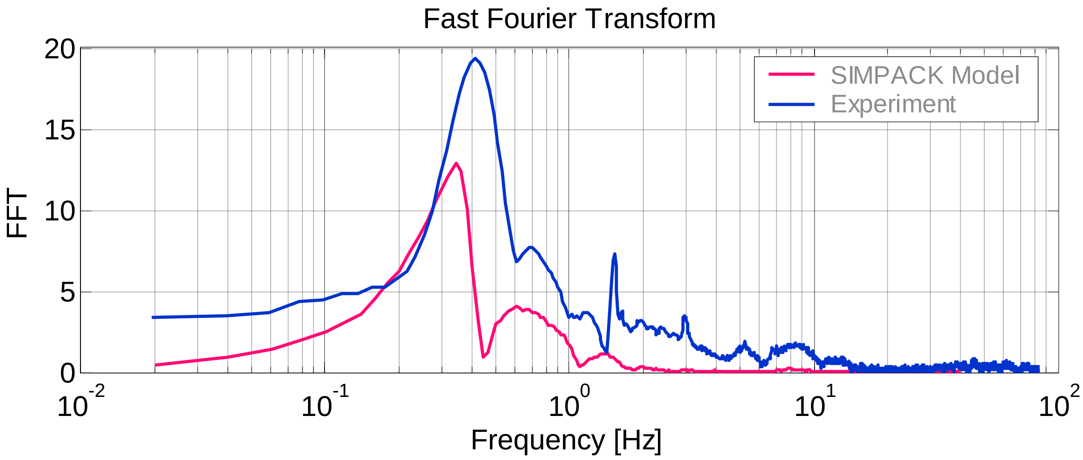

Fig. 3. Pantograph frequency response function (in blue: model, in pink: experiment)

ANALYSIS STAGE – SENSIBILITY STUDY OF THE DIFFERENT DESIGN PARAMETERS

Assessing current collection quality

Once the models were validated, comparative simulations were carried out. Among other results, the contact force acting between the pantograph's contact strips and the catenary was obtained, being an important parameter when assessing current collection quality [15, 19]. The force exerted by the pantograph must be high enough to prevent contact loss, and small enough to limit wear.

The contact force was then statistically processed as recommended by the European railway administrations [15, 21, 22]. The following, typical contact force statistics were determined: the mean value of the contact force, the standard deviation, the statistical maximum and minimum, the total number of contact losses, and the accumulated contact loss time.

Sensibility study and comparative results

As a next step, a sensibility analysis was carried out. In the sensibility study, models in which several specific design parameters had been doubled, were compared, one by one, to a reference model maintaining the original values. The parameters considered were the following: the area moment of inertia of the conductor rail cross-section calculated with respect to the vertical axis, I_{VER}, and the same with respect to the horizontal axis, I_{HOR}, the Young's modulus, E, the material's density, ρ, the supports' width, D, and the structural damping of the catenary, d.

As an example, Fig. 4 shows the contact forces obtained for the reference model and for a separate model in which the horizontal area moment of inertia, I_{HOR}, had been doubled, for a straight track of 20 m of length.

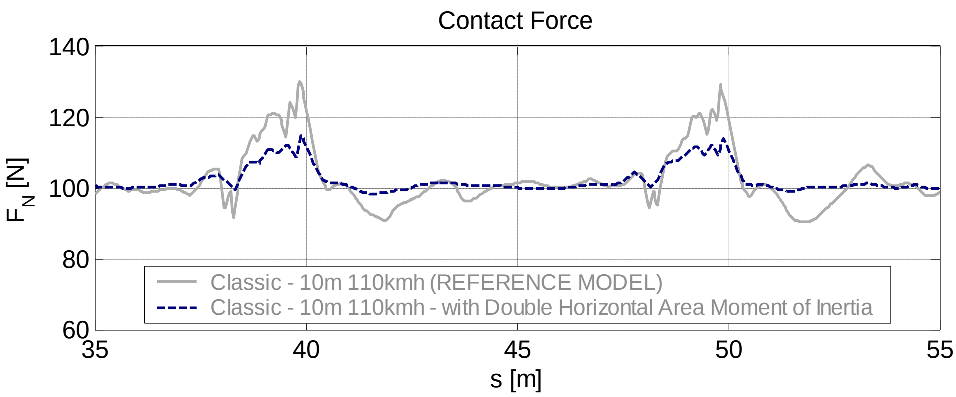

Fig. 4. Contact force for the reference model, and when doubling the area moment I_{HOR}

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It can be seen that the dynamic behaviour of the model with the doubled I_{HOR}-value is clearly superior to that of the reference model.

Table 1 shows the statistics of the contact force for both of the models presented in Fig. 4.

Contac Force STATISTICS			**Reference** Model	I_{HOR} Variation	Difference
Mean Value	F_m	[N]	102.4	102.1	-0.2%
Standard Deviation	**σ**	**[N]**	**8.3**	**3.7**	**-54.9%**
Statistic Maximum	$F_m+3\cdot\sigma$	[N]	127.2	113.3	-10.9%
Statistic Minimum	$F_m-3\cdot\sigma$	[N]	77.6	90.9	+17.2%
Actual Maximum	F_{max}	[N]	131.6	117.2	-10.9%
Actual Minimum	F_{min}	[N]	82.8	92.9	+12.1%

Table 1.Statistics for the reference model, and when doubling the area moment I_{HOR}

The standard deviation, σ, of the contact force is one of the main statistical variables that characterise the current collection quality. It is desirable that the standard deviation be small, since a homogeneous contact force favours the current collection process and reduces wear. Fig. 5 compares the standard deviation obtained for all of the cases treated in the sensibility study.

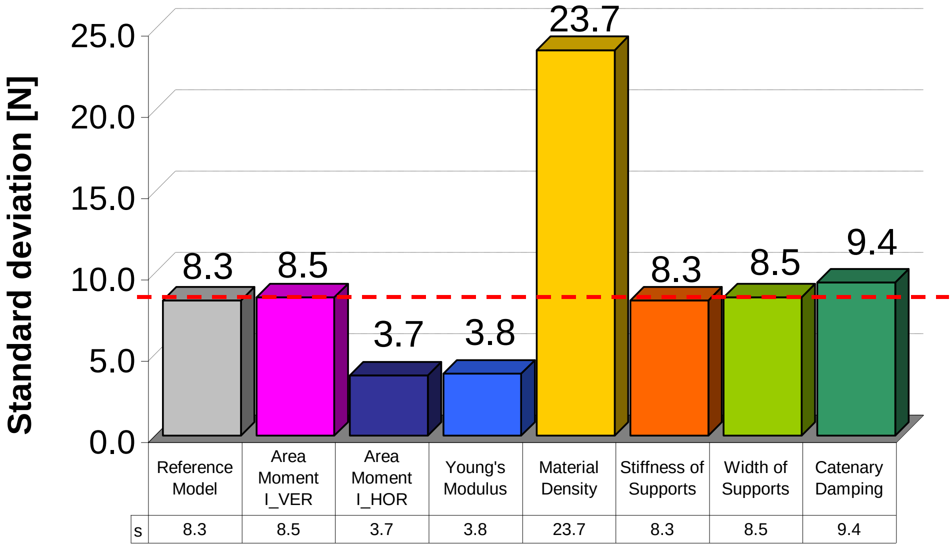

Fig. 5. Standard deviation, σ, for all the cases of the sensibility study

When analysing the results shown in Fig. 5, it can be seen that both an increase of the area moment of inertia, I_{HOR}, and of the Young's modulus improve the dynamic behaviour, while a denser material worsens the dynamic behaviour. The remaining parameters hardly have any influence on the dynamic behaviour of the whole system.

DESIGN STAGE – DESIGN OF A NEW OVERHEAD CONDUCTOR RAIL

In the sensibility study, three parameters were found suitable for improving the dynamic behaviour. For various reasons, only the parameter "area moment of inertia I_{HOR}" was chosen to be applied in the new design. By changing this parameter only, the area of the transversal or conducting section may be maintained and the same material (aluminium) may be applied for the conductor rail.

The most appropriate design in order to maximise the horizontal area moment of inertia, would be an I-shaped profile. Parting from this idea, a new profile was developed, whose transversal section, apart from increasing the area moment of inertia, I_{HOR}, would hold the contact wire firmly, as had been the case

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in the classic design. Furthermore, the force required to open the conductor rail during the assembly process should be low enough in order to avoid any plastic deformation of the material.

New design

Finally, a reversed "Y"-shaped profile was adopted for prototype manufacturing and for formal patent application. The new profile presents a horizontal area moment of inertia (I_{HOR} = 738 cm^4), which is a 74 % higher than that of the classic profile. However, the transversal area remains the same (A ≈ 2118 mm^2).This profile, called "METRO_730", is shown in Fig. 6.

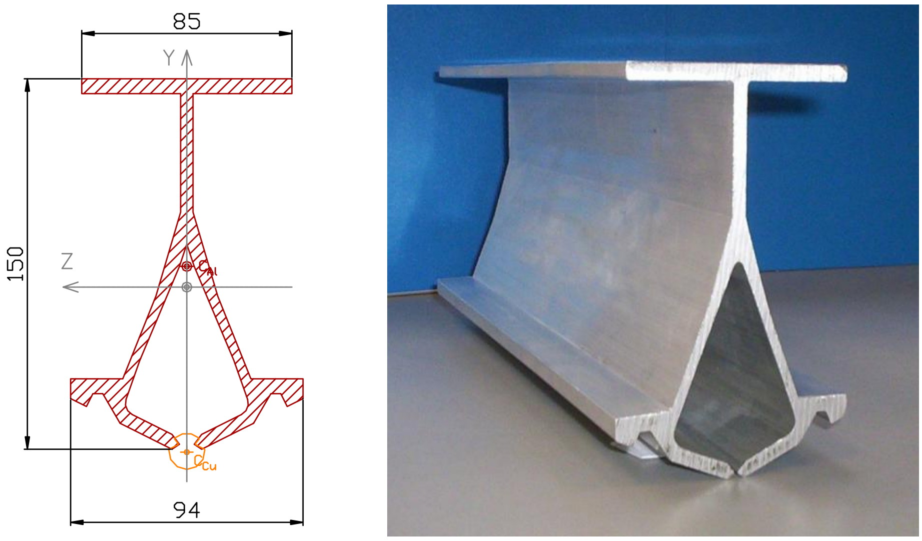

Fig. 6. New design: "METRO_730" (cross section and 3-D view)

New bridles

For the new profile proper joining bridles were also designed (Fig. 7). These bridles connect the aluminium pieces, forming a section overlap. As well as the conductor rail, the inner bridles are manufactured by aluminium extrusion.

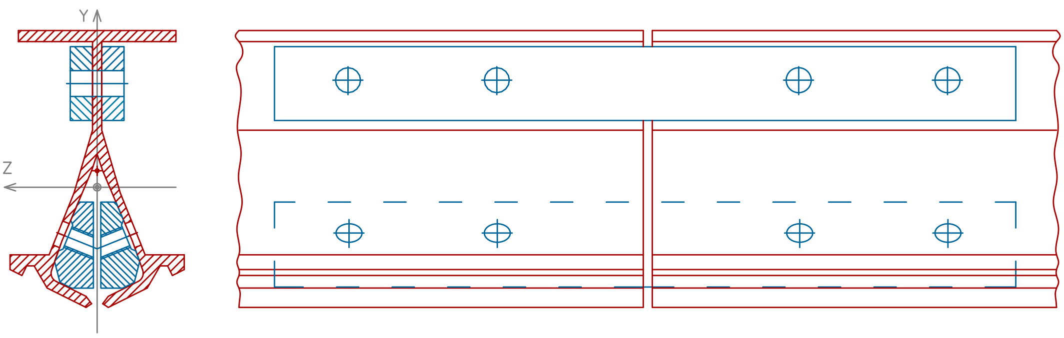

Fig. 7. Design of the new joining bridles

New section insulator

Section insulators are used to divide the power supply system into different electrical circuits or sections. Section insulators electrically separate a specific zone inside an overlap section, guaranteeing mechanical continuity and a smooth passing of the pantograph's collector strips.

An original section insulator for the new conductor rail, METRO_730, was developed (Fig. 8).

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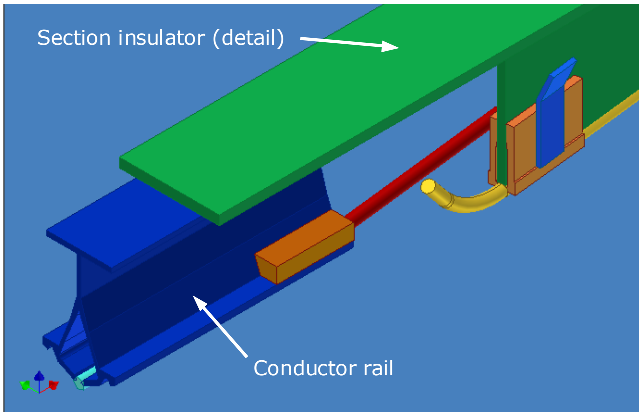

Fig. 8. New section insulator developed

Its main advantages are the compact design and its low weight. A more uniform wear of the contact wires and the pantograph strips is expected.

DESIGN STAGE – COMPARISON OF THE STATIC BEHAVIOUR OF BOTH PROFILES

From a structural point of view, the contact wire assembly process represents a critical situation, since it requires the temporary deformation of the conductor rail. The static behaviour of the new and the classic conductor rails was analysed and compared.

During the contact wire assembly process, the aluminium profile is opened by a special assembly carriage. This carriage has two pairs of wheels that fit into the grooves located in the lower part of the conductor rail (Fig. 8). Each pair of wheels is separated laterally, applying pressure to the aluminium rail, causing the flanges to open. This allows the insertion of the contact wire, as can be seen in the Fig. 9. This operation provokes a local deformation in the lower part of the rail.

In order to analyse the opening process, 3-D finite element models are needed. A 90-cm-long segment of the aluminium rail was sufficient in order to obtain valid results, since the deformations caused by the real carriage affect a 60-cm-long zone.

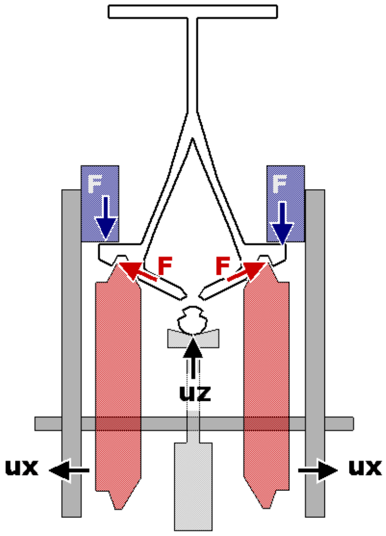

Fig. 9.Scheme of the contact wire assembly process

Although the opening forces have both vertical and horizontal components, only lateral forces were applied to the 3-D models. The vertical forces are eliminated by the reaction forces experiences in a second set of wheels resting on the horizontal plane located above the flanges (see Fig. 9). The lateral point loads were applied to two cross sections, being the distance between them equal to the spacing of

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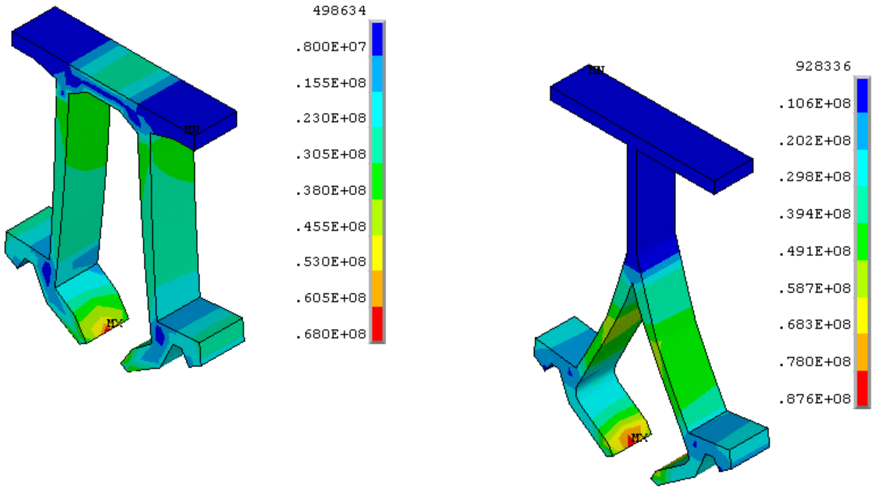
the carriage's two pairs of wheels. The carriage is placed in the mid-section of the modelled 90-cm-long conductor rail segment.

The results of this static analysis revealed that the stresses reached during the opening process are relatively low, reaching maximum values of 68 MPa and 88 MPa for the classic and the new design respectively. Fig. 9 shows the "Von Mises" stress distribution obtained for the section in which the loads were applied. The blue contours indicate the low stresses and the red ones the high ones.



Max. 68 MPa **Max. 88 MPa**

Fig. 10. Von Mises stress, in the classic (left) and new (right) profiles

Even though the maximum stresses reached in the new design are higher than the ones in the classic profile, their values still lie below the limit value for the yield strength, $\sigma_e = 216$ MPa (aluminium). Due to both of the reasons mentioned, a perfect behaviour during the contact wire assembly process was expected.

In addition, a destructive traction test was carried out in Metro de Madrid laboratories, analysing the behaviour of a prototype of the new conductor rail during the opening process. It was proven that the new conductor rail can be open enough in order to insert the contact wire, without suffering any kind of plastic deformation. A fatigue test was also performed, whose results were also found satisfactory.

DESIGN STAGE – COMPARISON OF THE DYNAMIC BEHAVIOUR OF BOTH PROFILES

In order to compare the dynamic behaviour of the new profile to the classic one, various simulations were realised in SIMPACK.

Comparison between the classic profile and the new design

In the following, a direct comparison between both profiles will be presented. The dynamic behaviour of both models was simulated for a 98-m-long straight overlap section with a nominal distance of 10 m between supports and a constant running velocity of 110 km/h.

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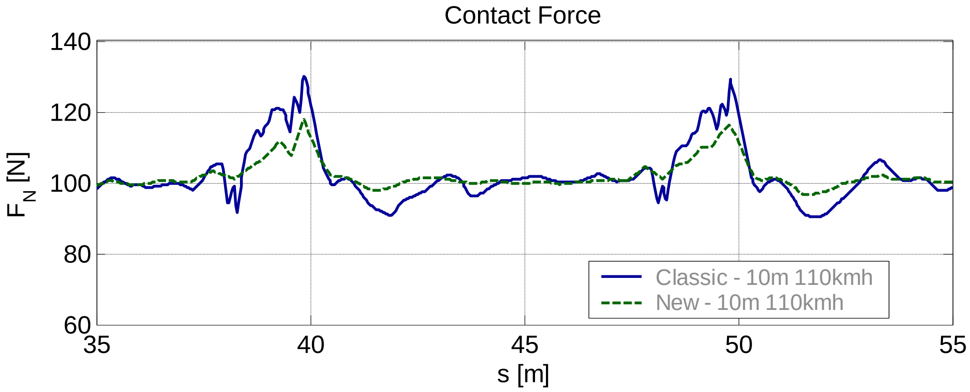

Fig. 11. Contact forces for the classic (-) and new (--) profiles (10m, 110 km/h)

It can be seen in Fig. 11 that the contact force of the new design has a smoother curve. A statistical analysis showed that the standard deviation of the contact force was reduced to almost half the original value, being the corresponding values for the classic and the new profiles:

$$\sigma_{classic} = 8.3 \text{ N} \qquad \sigma_{new} = 4.5 \text{ N}$$

It should kept in mind that low values for the standard deviation indicate a good dynamic behaviour of the interaction between pantograph and conductor rail.

Determination of the maximum distance between supports

Since the new design had a better dynamic behaviour than the classic one, it was wondered to what degree the distance between supports could be increased for the new conductor rail without obtaining worse results in the dynamic behaviour than the classic profile. Distances of 10, 12 and 14 m were simulated with the pantograph passing at a constant speed of 110 km/h. It could be shown that the dynamic behaviour of the new profile with 12 to 14 m between supports is similar to the one of the classic case with 10 m. Fig. 12 shows the contact force obtained when analysing these cases.

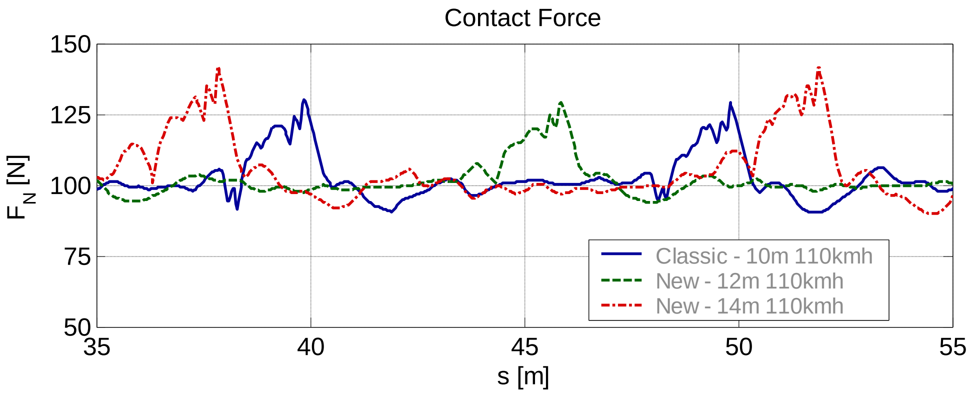

Fig. 12. Contact forces for 110 km/h

As can be seen in the figure, the peaks of the contact forces do not coincide for the three cases, since the catenary supports are spaced differently (10, 12 and 14 m) and the velocity is the same. Fig. 13 shows the corresponding standard deviation of the contact forces. The statistical results for both profiles are presented together, for distances between supports of 10, 12 and 14 m and a constant velocity of 110 km/h.

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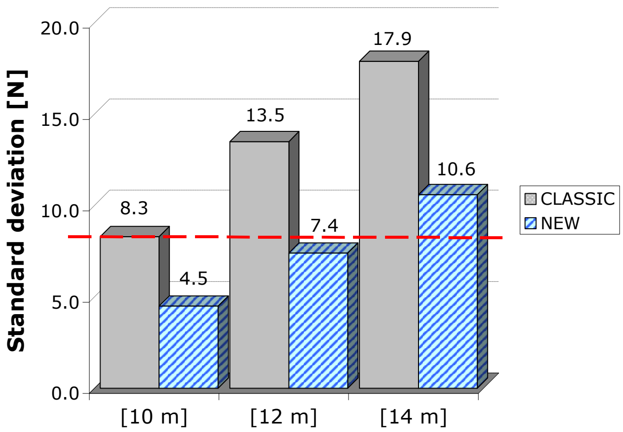

Fig. 13. Standard deviation of the contact force, for 110 km/h

As can be seen, the new profile at 12 m has a very similar response to the classic profile at 10 m. A slightly worse behaviour is obtained when increasing the separation between supports to 14 m.

Determination of the maximum running velocity

Another possibility in order to obtain the same dynamic behaviour for both profiles, was to increase the pantograph's running velocity. Running speeds of 110, 140, and 150 km/h were simulated for a constant support spacing of 10 m. It could be shown that with the new profile, running speeds of up to 150 km/h could be reached. Fig. 14 shows the contact force evolution obtained for three different cases.

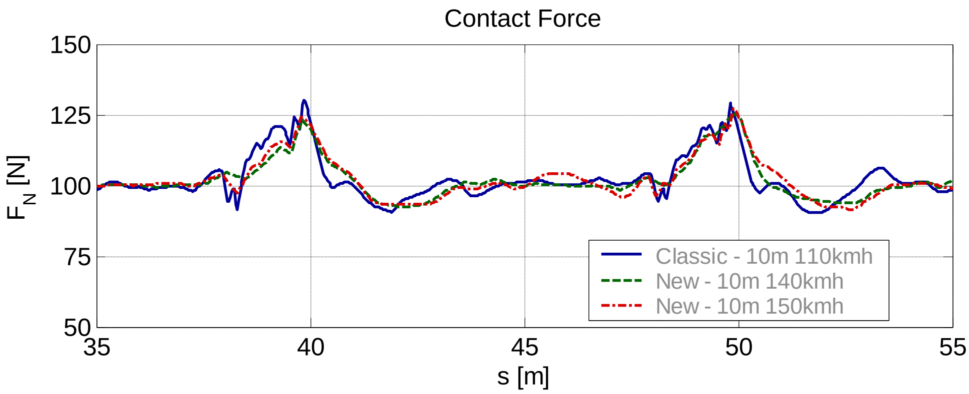

Fig. 14. Contact force for 10 m distance between supports

As can be seen, both conductor rails present a fairly similar behaviour at the velocities shown. However, the contact forces of the new profile are somewhat smoother. Fig. 15 shows the statistical results for the contact forces. As before, the standard deviations of both profiles are represented in the same graph, in this case for running speeds of 110, 140 and 150 km/h.

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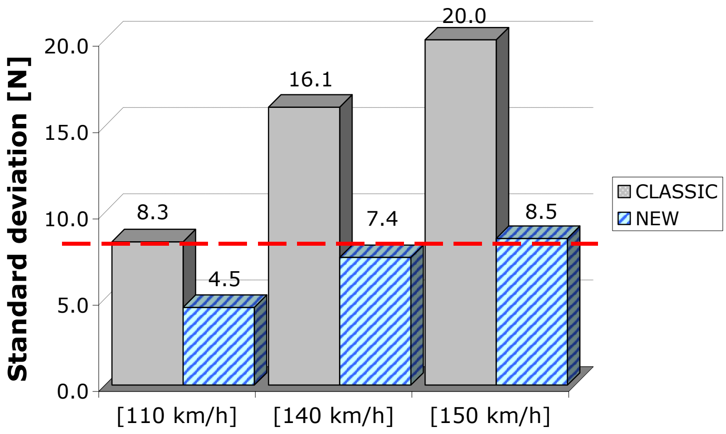

Fig. 15. Standard deviation of the contact force, for 10 m between supports

As can be seen, the standard deviation for the current profile at 110 km/h falls between the ones relating to the new profile at 140 and 150 km/h.

TESTING STAGE

Patent request

Considering the excellent results found in the previous simulations, Metro de Madrid and CITEF applied for a formal patent for the new designed conductor rail. This patent was officially accepted in December 2004 (European patent nº EP 1 484 214 A1) [13].

Prototype manufacturing

Metro de Madrid also requested the construction of a prototype. This prototype was recently installed in a test track sited in their own network, comprising a total length of 500 m.

Field tests

At the present time, the new overhead conductor rail is being tested. The correct performance of the whole system will be assessed under real service conditions. A field measuring process will be conducted, in which the data acquisition will be realised by a measuring pantograph developed by CITEF (Fig. 16).

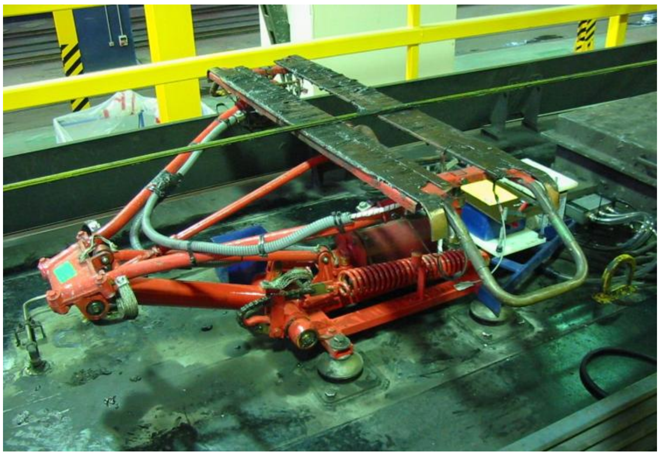

Fig. 16. Measuring pantograph

The measuring pantograph is equipped with load cells under both springs of the strip suspension, and with two accelerometers for recording the vertical movements of the pantograph head. By properly combining these signals, an indirect measurement of the contact force can be achieved.

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Although no definite experimental results are available yet, comparisons of first results reveal the superiority of the new design as was predicted in simulation. In a future publication, the authors will present the experimental results obtained.

CONCLUSIONS

A new profile for overhead conductor rail systems was designed. Its features are superior to that of the classic system primarily in use in the Madrid underground. During the development process, advanced modelling and simulation techniques were used. Particularly, a finite element modelling program was used for the catenary model, and a multibody systems simulation program for the pantograph model. A combined pantograph-catenary interaction model was set-up.

After fitting the models with experimental measurements, a sensibility study was performed over the different parameters that characterize the system. In this way, it was possible to select those design parameters whose variation led to a better dynamic performance of the combined system. The key parameter that was increased in the new design was the horizontal area moment of inertia which had given good results in the sensibility study.

Finally, a reversed "Y"-shaped profile was adopted for prototype manufacturing and for formal patent request. Static and dynamic simulations were realised, in order to test the new profile's quality. The simulation results showed the new design's superiority in comparison to the classic one.

The new conductor rail can be installed with greater distances between supports, on those underground lines or tunnel sections where the maximum running speed is fixed to 110 km/h. Otherwise, it is possible to attain higher running speeds maintaining the actual distance between supports of 10 m. It can be said that the new design improves simultaneously both the current collection and the economic efficiency. Therefore, is should be the new standard for overhead rail conductor installation, not only in Metro de Madrid, but also worldwide. As a matter of fact, Metro de Madrid has decided to install this new system in their future underground lines.

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